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December 21, 1999

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Ms. Magalie Roman Salas
Secretary
Federal Communications Commission
445 Twelfth Street, S.W.
Washington, D.C. 20554

Re: USA Digital Radio, Inc.
MM Docket No. 99-325

Dear Ms. Salas:

Enclosed for filing in the above-referenced proceeding is a copy of USA Digital Radio, Inc.'s ("USADR") recent report submitted to the National Radio Systems Committee ("NRSC"). This report on USADR's laboratory and field testing of its AM and FM In-Band On-Channel ("IBOC") Digital Audio Broadcasting ("DAB") system was recently submitted to the NRSC as part of the NRSC's evaluation of the improvements IBOC DAB will offer over existing analog radio broadcasting. The USADR report demonstrates its system offers superior audio quality over today's analog service, is immune to multipath, noise and signal interference and does not harm existing analog broadcasting.

USADR looks forward to working with the NRSC and the Commission to have IBOC DAB adopted as the digital standard for AM and FM radio. Any questions concerning this report should be directed to the undersigned.

Respectfully submitted,

AmAShm

Robert A. Mazer
Albert Shuldiner

Counsel for USA Digital Radio, Inc.

cc: Roy J. Stewart (MMB)
Dale N. Hatfield (OET)

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USA DIGITAL RADIO

Report on Laboratory and Field Testing Presented to the National Radio Systems Committee

USA Digital Radio, Inc.
8865 Stanford Boulevard
Suite 202
Columbia, MD 21045
(410) 872-1530

December 15, 1999

Table of Contents

This report summarizes the results of laboratory and field tests USA Digital Radio, Inc. ("USADR") conducted between May and December 1999 as part of its IBOC system development efforts. USADR has prepared this report to demonstrate its system is an improvement over current analog radio broadcasting in accordance with the guidelines established by the National Radio Systems Committee ("NRSC"). USADR conducted these tests using numerous facilities including (i) USADR's DAB laboratory in Columbia, Maryland; (ii) digital radio laboratories of Xetron Corporation in Cincinnati, Ohio; (iii) the independent laboratory test bed established for the USADR system at the headquarters of the Advanced Television Technology Center ("ATTC") in Alexandria, Virginia; (iv) WPOC-FM, Baltimore, Maryland; (v) WETA-FM, Washington, D.C.; and (vi) USADR's digital AM station in Cincinnati.

The results reported herein represent a snapshot of the USADR system at the time the tests were conducted. USADR's test program, however, is an ongoing process. In some cases, system improvements have been implemented after completion of certain tests and may not be reflected in test results. In other cases, ongoing system optimization efforts may change the results reported in these tests. Moreover, USADR has opted to provide only the level of information it views as necessary to demonstrate an improvement over analog. To protect proprietary information, USADR has not included additional information which would demonstrate the full range of features of USADR's system. Nonetheless, this report will allow the NRSC to conclude the baseline system parameters and results, even without further optimization, are an important and necessary enhancement over existing analog radio service.

The results of the tests show that USADR has developed a system that offers superior audio quality over today's analog service. In addition, the USADR system is immune to multipath and noise, providing for a much improved listening experience. In short, the system offers a compelling service upgrade for listeners and broadcasters without harming existing analog broadcasting.

USADR's ongoing test program has focused on several objectives. The tests have examined the existing analog environments in the AM and FM bands. In conjunction with USADR's system development efforts, the test program has been used to consider the merits of various technical solutions and tradeoffs for the implementation of IBOC. Most recently, the test program has focused on compatibility and performance tests of USADR's AM and FM systems.

The main text of this report contains an introduction about USADR, an overview of USADR's test program and a summary of the test results demonstrating that the USADR system is an improvement over existing analog broadcasting. Following the main text are a series of appendices which describe in detail (i) USADR's test program; (ii) the USADR IBOC DAB system; (iii) tests of the performance of the USADR system; (iv) compatibility tests of the USADR system; (v) independent testing of the USADR system conducted by the ATTC; and (vi) field tests conducted using WPOC-FM, WETA-FM, and USADR's AM test station in Cincinnati. The second volume of the report contains related audio and video reference material.

USADR acknowledges this report only contains a summary and analysis of the raw data USADR has compiled in its test program. Inherent in any summary is the risk of oversimplification or misunderstanding from lack of access to the underlying data. USADR encourages the NRSC to contact USADR with questions about this report to avoid misunderstandings or misinterpretations.

Any questions concerning this report should be directed to E. Glynn Walden, Vice President, Broadcast Engineering, USA Digital Radio, Inc., 8865 Stanford Boulevard, Suite 202, Columbia, Maryland 21045, (410) 872-1526.

I. Background on USADR

In 1991 USADR conceived IBOC technology and since that time has been a pioneer in the development of DAB for terrestrial radio. USADR is backed by a coalition of interests including broadcasters, equipment manufacturers and research centers in the United States and abroad. Twelve of the nation's largest radio broadcasters, including the ten largest, own USADR. Owners include ABC, AMFM, CBS, Chase Capital Partners, Citadel Communications, Clear Channel, Cox Radio, Cumulus Media, Emmis Communications, Entercom Communications, Gannett, Hispanic Broadcasting, Radio One and Sinclair Broadcasting Group. USADR has assembled a board of directors of prominent radio broadcasters, government regulatory and emerging technology experts, including Mel Karmazin of CBS, Jimmy de Castro of AMFM and Alfred Liggins of Radio One. USADR's owners have coverage in 196 of the 270 Arbitron-rated markets, access to 200 million listeners and combined revenues equating to 46% of the radio industry's total revenues.

Other broadcasters representing more than 500 stations are participating in USADR's Early Adopter Station Enhancement ("EASE") program. The EASE program, targeted at small and mid-size radio stations, offers to help broadcasters stay abreast of IBOC developments, provides station assessments about compatibility of equipment with USADR's system and distributes announcements of key milestones. Of these EASE participants, more than 35% come from non-Arbitron-rated markets.

USADR is building on this ownership base and assembling the broad business coalition necessary to ensure radio's rapid transition to a digital future. It has entered into joint technology and marketing agreements with radio broadcast transmission equipment manufacturers, including Andrew Passive Power, Broadcast Electronics, Continental Electronics, Energy-Onix, Nautel, Orban, QEI, Shively Labs, and Telos/Cutting Edge; DSP chip manufacturer Texas Instruments; and receiver manufacturer Kenwood. Each member of this growing coalition has agreed to develop coordinated strategies for the market launch of IBOC technology and their associated products. Additionally, USADR has several development partners including Fraunhofer Institut für Integrierte Schaltungen (IIS) which is coordinating establishment of an international standard for Advanced Audio Coding ("AAC"), Xetron for AM system development and testing, and Bittware for SHARC technology and receiver/exciter boards for development test efforts.

Moreover, under an agreement announced yesterday between USADR and Digital Radio Express ("DRE"), DRE will support efforts to commercialize USADR's IBOC DAB system. The companies will cooperate in the development of USADR's IBOC DAB technology and the regulatory process required for its adoption in the United States. DRE will focus its business on data ventures, including specialized data applications for USADR's system.

Over the last eight years, USADR has developed a comprehensive understanding of the AM and FM broadcasting environments through identification of system requirements and the completion of critical tests and complex simulations. As a result, its IBOC DAB solution is designed to be a total systems approach, combining multiple digital signaling techniques with coding algorithms to deliver a superior performing, robust digital radio service. Over forty world-class engineers and scientists are presently working on USA Digital Radio's IBOC DAB system and the company holds 27 patents, with numerous pending patent applications covering broad aspects of IBOC DAB technology.

USADR's mission since it was founded has been, and continues to be, the introduction of IBOC DAB which will allow for a rational transition from existing analog to digital broadcasting for broadcasters and listeners. Because IBOC allows for the introduction of digital broadcasting along with the existing analog broadcast, IBOC is spectrally efficient, avoids the need for new spectrum, facilitates the upgrade to digital in the course of normal equipment replacement cycles, and does not require any adjustments in listener behavior in order for the public to find a favorite radio station on the dial.

The development of any IBOC system requires various tradeoffs between the amount of audio programming and auxiliary services provided, the quality of the audio and the robustness of the system, and the need to create a strong digital audio service without disrupting existing analog broadcasts. USADR has designed its system to maximize the benefits for listeners and broadcasters and provides for the smoothest possible transition to digital broadcasting. The system enhances audio quality and robustness to improve the listening experience. At the same time, USADR has emphasized flexibility to enable broadcasters and consumers to decide their own timetable for upgrading to IBOC DAB.

II. Description of Test Program

USADR's report is based on the results currently available from USADR's laboratory and field testing of its IBOC DAB system. USADR initiated its test program in 1998 as part of its development work on IBOC DAB. Initial simulations and preliminary test results were included in USADR's Petition for Rulemaking filed with the Federal Communications Commission ("FCC") on October 7, 1998. Based on the NRSC's laboratory guidelines and field test guidelines, USADR modified its test program for 1999 to address many of the tests recommended by the NRSC. Although extensive test results are attached, additional tests are scheduled for 2000 as USADR continues to optimize its system.

Compatibility lab tests were performed at Xetron and the ATTC. These tests compared the signal-to-noise ratio of various receivers in the presence of analog interference against the results obtained from the addition of hybrid IBOC signals to the host station or adjacent channel stations.

In field tests conducted using WPOC-FM, compatibility is demonstrated in the form of recordings depicting the quality of the recovered audio with and without the hybrid IBOC signal on the host station and its first adjacent channel stations.

Performance lab tests were conducted at USADR's DAB laboratory to demonstrate the performance of the IBOC system when challenged by interference, multipath and noise. Lab results were confirmed in the field using WETA-FM and USADR's experimental AM station in Cincinnati.

III. Test Results

USADR's test program demonstrates the USADR system offers a compelling improvement over existing analog broadcasting by providing superior audio quality and robustness within a station's service area. The USADR system offers a higher audio quality than existing analog broadcasting. In addition, the USADR system's unimpaired digital coverage extends to a point where analog is degraded. Laboratory tests also confirm the USADR system will not cause audible interference to either the host analog or co-channel and adjacent channel non-host analog signals within a station's listening area. At the same time, the USADR system offers acquisition performance, stereo separation, and a level of flexibility equivalent to analog broadcasting in order to address listener expectations. The overall conclusion to be drawn from these extensive tests is that the USADR broadcast system is superior to the current analog broadcast system.

A. Audio Quality

The results of USADR's test program demonstrate IBOC will offer an audio quality superior to that offered by existing analog radio. USADR and ATTC, as part of its independent test program, attempted to use an objective perceptual audio and speech quality measurement software package to conduct subjective listening tests. Unfortunately, the software evaluation tool that was used did not provide consistent results; therefore the data is not available for this report. Instead, USADR has included as attachments to this report the actual sound recordings of analog and digital made during the unimpaired audio tests and the USADR field tests. These audio recordings will allow the NRSC to make its own evaluation of the sound quality of the USADR system and to conclude the system is an enhancement over existing analog FM and AM.

B. Service Area and Durability

The USADR system will offer high quality digital coverage with increased robustness throughout a station's current service area. USADR's laboratory and field tests have confirmed the IBOC system's service area will allow for a significant enhancement of service to the public over that provided by existing analog service.

Because the USADR system incorporates a blend from digital service to analog, the system will always provide coverage as extensive as that offered by existing analog. Of greater interest, however, is the extent of digital coverage before the blend to analog. USADR's laboratory tests analyzed the performance of the digital system with Gaussian noise (as a baseline), with multipath fading and in the presence of first adjacent, second adjacent and co-channel interference. In each case, the tests examined the quality of digital coverage until the threshold of audibility ("TOA") of signal degradation and compared that against the quality of analog at the same point. The tests demonstrate that the digital system provides unimpaired digital coverage to the TOA. At the point where the digital signal begins to degrade, the corresponding analog audio itself exhibits audible degradation. This implies that the analog audio is degraded at signal levels where digital audio degradation is not yet perceptible. As a result, up to the point of digital TOA, the performance of the digital signal surpasses that of the existing analog signal.

USADR's field tests confirm the benefits of the digital system. The tests which were conducted at digital power levels below 500 watts, demonstrated significant coverage for both AM and FM, depending on terrain, noise and interference. Within that coverage area, the USADR system provides audio, free of degradation due to the noise, multipath and interference that is characteristic of existing analog. Moreover, there is no muting and virtually no blending. Outside that area, there is a region where the system blends back and forth between digital and analog. This begins near the 45-dBu signal strength contour for FM and 3mV/M for AM. The IBOC receiver, even while blending, delivers audio quality which is superior to the analog available at that location. In fact, the analog audio received from the IBOC receiver often sounds better than audio from current analog receivers due largely to proprietary FM demodulation techniques USADR developed to mitigate the effects of multipath. Beyond the point of failure of the digital signal, blend will allow the listener to receive the degraded analog signal that remains available at that point.

C. Acquisition Performance

The USADR system provides instant acquisition performance for the listener. The performance, from the listener's perspective, will be identical to current acquisition expectations for existing analog broadcasts. The listener will experience instant acquisition both for initial tuning of stations and for re-acquisition of lost signals.

USADR's system incorporates both analog and digital components. The receiver instantly acquires the analog signal, providing the listener with instant access to station programming. At the same time, the system searches for the digital signal. Upon frequency acquisition, the system tracks the digital symbols. Upon frame lock, the receiver blends from analog to digital. Although the total digital acquisition process takes several seconds, the listener is able to receive analog audio during that time.

D. Auxiliary Data

DAB, in its most basic form, is simply a digital bit-stream transmitted in the AM and FM bands. Because the digital bit stream can be devoted to either audio or data, the USADR system has the capability to provide data services in addition to the primary audio signal. In order to achieve the USADR system's design requirement of robustness and improved audio quality, a majority of the capacity of the USADR system is devoted to the primary audio signal. However, the system supports auxiliary data on FM, which greatly upgrade the existing SCA services, and a low rate data capability on AM.

The USADR FM system will allow broadcasters to provide ancillary services. The broadcaster can select a guaranteed data throughput by trading off audio quality for a dedicated data bit stream. For example, if the broadcaster runs a talk show, 64 kbps could be sufficient for audio, therefore, 32 kbps could be set aside for data. The AM system also has this same capability, only with a smaller amount of data throughput.

32 kbps of "opportunistic" data, available depending on audio programming can be sporadically multiplexed with the audio on a priority basis or when spare bandwidth is available on the FM system. For example, during quiet segments, commercials that do not require CD-like quality audio or talk shows, bits can dynamically be used for data. The AM system also features this same capability, only with a smaller amount of throughput.

E. Edge of Coverage

USADR's system is designed to provide listeners with the same performance at the edge of coverage as listeners have come to expect from analog broadcasts. Typically, digital systems experience muting at the edge of coverage. In essence, the signal is nearly unimpaired until it completely fails. This has been termed the "cliff effect." The USADR system blends from digital to analog at the edge of coverage to provide the listener with more graceful degradation than can be provided with the loss of the digital signal. When the digital signal fails, the system gracefully blends to analog. Although analog may be severely degraded at the point of failure of the digital system, the blend to analog can extend the coverage area until the listener deems the analog quality to be unlistenable.

F. Stereo Separation

The USADR FM system provides full stereo separation to the extent of digital coverage. This is superior to existing analog receivers which frequently blend to mono within the core service area due to multipath, noise or interference. After the blend to analog at the edge of coverage, stereo separation is the same as that for existing analog. The USADR AM system provides stereo information within the digital coverage area, blending to analog at the edge of coverage similar to the FM system.

G. Flexibility

The USADR system has been designed to maximize flexibility for listeners, broadcasters, and equipment manufacturers. Because the USADR system can accommodate the new digital signal without adversely impacting existing analog broadcasts, broadcasters will be able to upgrade to digital at their own pace while retaining current analog service. The USADR system also is designed to facilitate future upgrades without disruptions to analog broadcasts. The system will permit the introduction of new features, such as data, without obsoleting the digital radios in the market prior to any such introduction. This backward compatibility will promote consumer acceptance of IBOC since consumers know their radios will continue to work in the future.

H. Host Analog Signal Impact

DAB power should be maximized to provide digital coverage consistent with existing analog service while at the same time minimizing impact on the host (and adjacent channel) analog signal. USADR's tests of host compatibility measured the degradation introduced to the host analog signal by its IBOC DAB sidebands. The tests measured the audio Signal Noise Ratio ("SNR") of the host FM signal with and without IBOC DAB signals, in-fading and non-fading environments. The test was performed at weak, moderate and strong signal levels and with ambient noise temperatures of 10,000K and 100,000K.

USADR's tests demonstrate a car stereo performs consistently better than a boombox and home HiFi, even in an all-analog environment, presumably because of superior filtering. However, all three radios were virtually unaffected by the addition of DAB at any level, regardless of the signal level or environment.

USADR confirmed these results in compatibility field tests conducted using WPOC. In those tests, the station's analog signal was measured as the digital signal was switched on and off. These tests showed no perceptible difference in the recorded audio upon addition or removal of DAB sidebands. The addition of DAB was not audible in a clean, high-signal, interference-free environment. The digital sidebands will cause less host interference in lower signal level environments due to noise and interference masking effects.

I. Non-Host Analog Signal Impact

USADR's tests of first adjacent compatibility measured the degradation introduced to the desired analog signal by a first-adjacent hybrid IBOC signal. USADR measured the analog audio SNR of the desired IBOC signal in the presence of a first adjacent signal, with its DAB turned on and off for both AM and FM signals. It also assessed the audibility of the first adjacent signal when listening to both quiet and modulated desired FM signals. In addition, the test recorded the levels of the first-adjacent DAB sidebands at which the TOA and Point of Failure ("POF") were reached for each of the receivers, with both quiet and modulated desired FM signals. The test was performed at weak and moderate levels with ambient noise temperatures of 10,000K and 100,000K and under fading and non-fading environments for FM and screen room low noise environments for AM.

The host compatibility tests indicated that better filtering in the car stereo results in better immunity to noise induced by DAB sidebands. However, the car stereo holds no clear advantage in rejection of first-adjacent DAB sidebands, due to their spectral occupancy under the desired channel. In fact, for both AM and FM the introduction of DAB to a –6-dB first adjacent signal has very little effect on audio SNR of the desired analog signal (less than 3 dB in even the cleanest environment), regardless of the receiver. Clearly, degradation due to the environment, such as noise and the analog portion of first adjacents, dominates over any additional noise added by baseline DAB. This finding was further validated in subjective audio tests, which showed that, with audio on the desired channel, the addition of baseline DAB to a –6-dB first adjacent signal is virtually inaudible under all signal strengths and environments.

The FM first adjacent compatibility results were confirmed in the field. USADR measured the impact of the WPOC digital sidebands on WMMR's and WFLS's 54-dBu and 40-dBu FCC contours. These points were chosen because they represent the strongest impact on the first adjacent stations. The tests demonstrated that there was no perceptible difference in the recorded audio upon addition or removal of the digital sidebands from WPOC except at WFLS's 40dBu which is WPOC's 74 dBu. At this location, because of the large disparity in signal strengths, a performance difference can be heard. However, the reception without WPOC's DAB "on" of WFLS is so poor, it is not listenable. Therefore, USADR has concluded the addition of digital sidebands to the first adjacent analog signal does not introduce audible degradation to the desired signal within its listenable coverage area.

In summary, USADR's laboratory and field tests represent a series of important tests in proving that this IBOC system offers the benefits of digital broadcasting. The USADR system is a quantitative enhancement over existing analog AM and FM broadcasts.

Appendix A

Appendix A

Test Plan Overview

The USADR test plan is designed to compare the performance of its IBOC system to the existing analog AM and FM broadcast services and to demonstrate that IBOC is an improvement over analog. As part of USADR's on-going system evaluation, extensive testing was conducted in the laboratory and field. These tests were primarily designed to evaluate IBOC compatibility and performance against analog. IBOC systems are designed to work within the existing broadcast infrastructure requiring compatibility with the existing analog service and performance under the existing interference and channel conditions.

Compatibility tests were performed to demonstrate the impact of the IBOC system on the analog host and the adjacent channel broadcasts. The compatibility lab tests were performed at Xetron Corporation in Cincinnati, Ohio and at the Advanced Television Technology Center ("ATTC") in Alexandria, Virginia. These tests compared the signal to noise ratio of various receivers in the presence of analog interference against the results obtained from the addition of hybrid IBOC signals to the host station or adjacent channel stations. Additionally, in the case of an automotive FM radio, the tests were repeated with multipath applied to both the desired and undesired signal. In the FM field testing program, compatibility is demonstrated in the form of recordings depicting the quality of the recovered audio with and without the hybrid IBOC signal on the host station and its first adjacent channel stations.

Performance tests were performed in the USADR laboratories in Columbia, Maryland and on licensed commercial and non-commercial radio stations to demonstrate the performance of the IBOC system when challenged by interference, multipath, and noise. The challenges to an IBOC system are interrelated, with interference, noise, and multipath each contributing to the extent to which the IBOC signal can be received. The relationships are not linear, and various experiments were included to test the performance with varying degrees of impairments and interference. Laboratory performance measurements of the USDAR IBOC receiver are presented in the form of Block Error Rates ("BER") with a BER of 1% representing the threshold of audibility of the AAC codec. Field testing of the performance of the IBOC system is performed under real world conditions that subject the system to a larger number of variables than is possible in the laboratory. Performance information obtained from field tests determines at what contour a digital portion of the IBOC signal can be received, frequency of blending, and the robustness of the overall system in the presence multipath, channel impairments, interference and noise.

USADR's field testing program tests an IBOC receiver under mobile conditions. USADR has outfitted three test vans with spectrum analyzers, GPS receivers, IBOC receivers, 8 channel digital audio recorders and a computer-based data collection system. Interference studies were conducted to guide the development of the test routes. The routing of the test vans was laid out in such a way as to challenge the system in as many of the test conditions as possible. The exact routing of the radials was optimized to enable the van to cover areas of multipath, interference, and to be routed through urban, suburban, highway, and low rise residential areas.

USADR's field test report details portions of the compatibility testing USADR conducted on WPOC, 93.5 MHz, Baltimore, Maryland, and performance testing on WETA, 90.9 MHz, Washington, D.C. In the performance tests, the van traversed the routes while recording the status of the digital receiver (analog or digital reception), the level of the upper and lower 1st and 2nd adjacent channels, GPS location, distance from the transmitter and digital audio recordings of the Delco car radio and the USADR IBOC receiver.

First adjacent channel compatibility testing was conducted with WPOC's transmitter broadcasting the USADR IBOC signal. Tests were conducted at fixed locations representing the 54 dBu and 40 dBu contours of first adjacent stations WFLS, 93.3 MHz, Fredricksburg, Virginia and WMMR, 93.5 MHz, Philadelphia, Pennsylvania. Three receivers were tested at each location. Audio recordings of each receiver were made while the WPOC digital signal was switched on and off.

The host compatibility tests were conducted on WPOC. A location close to the transmitter site was chosen for analog compatibility tests of digital crosstalk into the host analog receiver. The audio of four receivers was recorded while the WPOC digital signal was switched on and off.

USADR makes extensive use of both laboratory and field testing programs in the evaluation and development of its IBOC system. The laboratory tests are useful in establishing the quantifiable limits of the IBOC system's performance under controlled conditions that yield repeatable results. Field tests yield more qualitative results and vary depending on multiple real world factors, making it more difficult to repeat results for single tests. Laboratory information can be used most effectively for coverage predictions and establishing the protection ratios needed in digital broadcasting. Although laboratory measurements will serve as the benchmark of IBOC's performance, field tests yield valuable data and present testing scenarios that can never be duplicated in the laboratory.

Preceding each test category will be a section devoted to the conclusions, procedures, equipment used, and the purposes of each test segment.

Appendix B

Appendix B

FM Hybrid IBOC DAB System Description

1. System Overview

IBOC technology provides a means of introducing digital audio broadcasting ("DAB") without the need for new spectrum allocations for the digital signal. USADR's FM hybrid mode allows the station to simultaneously broadcast the same programming in analog and digital. Although the level of the digital signal in the hybrid mode must be limited to accommodate the analog broadcast, the hybrid system will still afford an upgrade over existing analog service by providing enhanced audio fidelity, improved signal robustness, and expanded auxiliary services.

1.1. FM Hybrid IBOC Waveform

The FM hybrid IBOC spectrum is shown in Figure B-1. Low-level digital sidebands are added to each side of the analog signal. The bandwidth is limited to $\pm$200 kHz from the center frequency. USADR has conducted simulations, analyses, laboratory compatibility tests, and field tests which verify that restricting the digital subcarriers to the 70-kHz regions between 129 and 199 kHz from the center frequency on either side of the analog spectrum minimizes interference to the analog host and adjacent channels without exceeding the existing FCC spectral mask. This bandwidth is wide enough to support a robust hybrid IBOC service with virtual CD-quality audio that mirrors the coverage of existing analog radio stations.[1]

The dual-sideband structure enables the use of frequency diversity to further combat the effects of multipath fading and interference. The baseline hybrid system simultaneously transmits 96 kbps of error-protected digital audio information, plus auxiliary services, on each DAB sideband. Each sideband has all the information and thus can stand alone. However, when neither sideband is corrupted, advanced FEC coding techniques allow the combination of both sidebands to provide additional signal power and coding gain.

Figure B-2 shows a scenario in which a desired hybrid IBOC signal and an upper first-adjacent hybrid IBOC interferer can co-exist. The figure shows that there is no interference between the hybrid digital sidebands. However, the analog portion of the first adjacent hybrid signal may interfere with the upper digital sideband of the desired hybrid signal. In an effort to reduce analog interference to the digital sidebands, USADR has developed a technique known as First Adjacent Cancellation ("FAC"). In addition, the use of frequency diversity and advanced FEC coding techniques further improves performance of the desired digital signal under these conditions.[2]

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1 Refer to the USADR field test results detailed in Appendix H.

2 Refer to the USADR laboratory performance test results detailed in Appendix C.

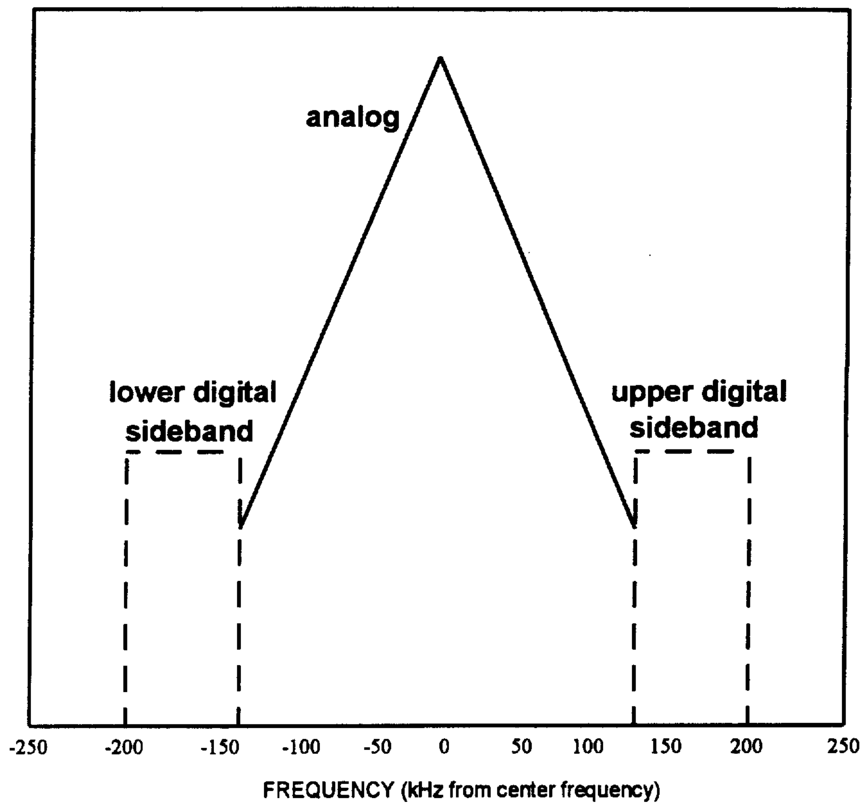

Figure B-1 - FM Hybrid IBOC Power Spectral Density

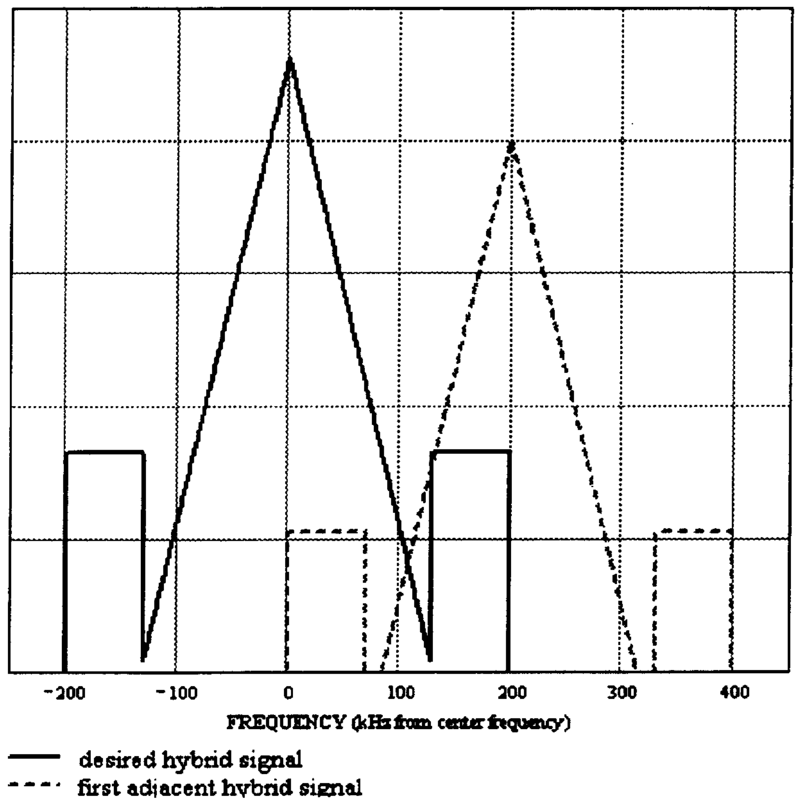

Figure B-2 - Hybrid First-Adjacent Interference Scenario

2. System Design

The USADR FM hybrid IBOC DAB system is comprised of four basic components: the modem, which modulates and demodulates the signal; the codec, which source encodes and decodes the audio source signal; forward error correction ("FEC") coding and interleaving; and blending. All of these core functional areas have been designed and integrated to produce an FM hybrid IBOC DAB system of superior quality.

2.1. Modulation Technique

USADR evaluated several modulation techniques for its FM IBOC DAB system before selecting Quadrature Phase Shift Keying ("QPSK"). QPSK affords robust performance while providing sufficient throughput for virtual CD-quality digital audio. It permits the use of advanced FEC coding techniques which exploit knowledge of the non-uniform interference environment. QPSK is also simpler and more robust than higher-order forms of modulation, especially in a multipath environment. Since QPSK has a bandwidth efficiency of two bits per second per Hertz, it supports an information bit rate that is sufficient for transmission of virtual CD-quality audio in the bandwidth available.

USADR compared multi-carrier versus single-carrier approaches to transmit the digital signal, and chose a multi-carrier approach called Orthogonal Frequency Division Multiplexing ("OFDM"). OFDM is a scheme in which many QPSK-modulated subcarriers can be frequency-division multiplexed in an orthogonal fashion such that each subcarrier does not interfere with its adjacent subcarriers. OFDM offers a high level of robustness in a multipath channel.

When combined with FEC coding and interleaving, the digital signal's robustness is further enhanced. The OFDM structure naturally supports FEC coding techniques that maximize performance in the non-uniform interference environment. The most important coded bits can modulate OFDM carriers that are located in the most protected regions of the channel.

2.2. Source Coding

CD digital audio has a data rate of 1.4112 Mbps (44,100 16-bit samples per second, for left and right channels). The FM channel bandwidth does not have the capacity to support a sufficiently high data rate to provide uncompressed CD-quality audio. As a result, an audio codec (coder-decoder) compression technique must be employed. The audio codec is a source-encoding device that removes redundant information from a digital audio signal in order to reduce the bit rate, and hence the bandwidth required to transmit the signal. The codec must perform this information rate compression while preventing the generation of perceptible artifacts.

USADR uses the AAC codec in its IBOC DAB system. The AAC codec compresses the CD bit stream to 96 kbps, delivering audio that the listener will perceive to be virtually the same quality as a CD. Use of the AAC codec meets the raw throughput requirements of the modulation and FEC coding techniques. Also, special error concealment techniques employed by the codec help to ensure graceful degradation of the received digital signal for operation in an impaired channel. In addition to its ability to meet the USADR system's audio compression requirements, AAC offers the advantage of being an open system based on the MPEG family of ISO standards.

AAC is the latest MPEG standard on perceptual audio coding and is part of the world-wide MPEG family of audio and video standards.[3] Much of the work on AAC was done by Fraunhofer, AT&T, Dolby Labs, and Sony, all leading experts in audio compression technology. It builds upon the existing MPEG Layer-3 standard by further optimizing coding efficiency.

AAC is a very flexible coding scheme, supporting data rates above 8 kbps. It can encode mono and stereo input data, as well as multichannel data (up to 48 channels). It is used for a wide

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[3] MPEG is the Moving Pictures Expert Group, working under the joint direction of the International Standards Organization ("ISO") and the International Electro-Technical Commission ("IEC"). Its main goal is the standardization of audio and video coding schemes. MPEG AAC was standardized as ISO 13818-7 in April 1997.

range of applications, from internet audio to multichannel surround sound. The high coding efficiency makes AAC attractive, especially for applications with very high quality demands or very limited transmission bandwidth.[4] Even though the basic structure of AAC is similar to previous audio coding techniques, including the commonly used MPEG Layer 3, AAC contains numerous innovations which are particularly helpful for the implementation of DAB. The crucial differences between MPEG AAC and its predecessor MPEG Layer-3 are as follows:

- *Filter Bank*: In contrast to the hybrid filter bank of MPEG Layer-3, which was chosen for reasons of compatibility but ultimately displayed certain structural weaknesses, MPEG AAC uses a plain Modified Discrete Cosine Transform ("MDCT"). Together with the increased window length (2048 instead of 1152 lines per transformation), the MDCT outperforms the filter banks used in previous coding methods.

- *Temporal Noise Shaping ("TNS")*: A true novelty in the area of time/frequency coding schemes, TNS shapes the distribution of quantization noise in time by prediction in the frequency domain. Voice signals in particular experience considerable improvement through TNS.

- *Prediction*: This is a technique commonly used in the area of speech coding systems. It benefits from the fact that a certain type of audio signal is easy to predict.

- *Quantization*: By allowing finer control of quantization resolution, the given bit rate can be used more efficiently.

- *Bit-Stream Format*: The information to be transmitted undergoes entropy coding in order to keep redundancy as low as possible. The optimization of these coding methods, together with a flexible bit-stream structure, has made further improvement of the coding efficiency possible.

During the standardization process, MPEG performed numerous listening tests to assess the audio quality of AAC. It is difficult to specify audio-coded performance in terms of traditional audio measurement techniques such as frequency response, distortion, and dynamic range; therefore, audio codecs are psychoacoustically compared against a CD reference. In these double blind tests, human testers are given the opportunity to compare compressed and non-compressed segments of the same selection and make judgments as to the quality of the compressed segment. In tests designed to replicate the worst case signals, the AAC codec at 96 kpbs has proven to be almost indistinguishable from the original selection. For the most extreme cases, the difference in the compressed signal is audible, but not considered a major issue for listeners. These tests use what is essentially a short audio clip played over and over to train the listener. In other words, while listening to 96 kbps AAC-encoded audio with high quality headsets, the average listener will not be able to distinguish between it and the original CD unless a short music selection is played

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[4] AAC has been chosen as the audio coding standard for the Japanese HDTV system, which will be introduced in 2000.